Interplanetary Probe Workshop-10
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THE CHALLENGES OF CREDIBLE THERMAL PROTECTION SYSTEM RELIABILITY QUANTIFICATION

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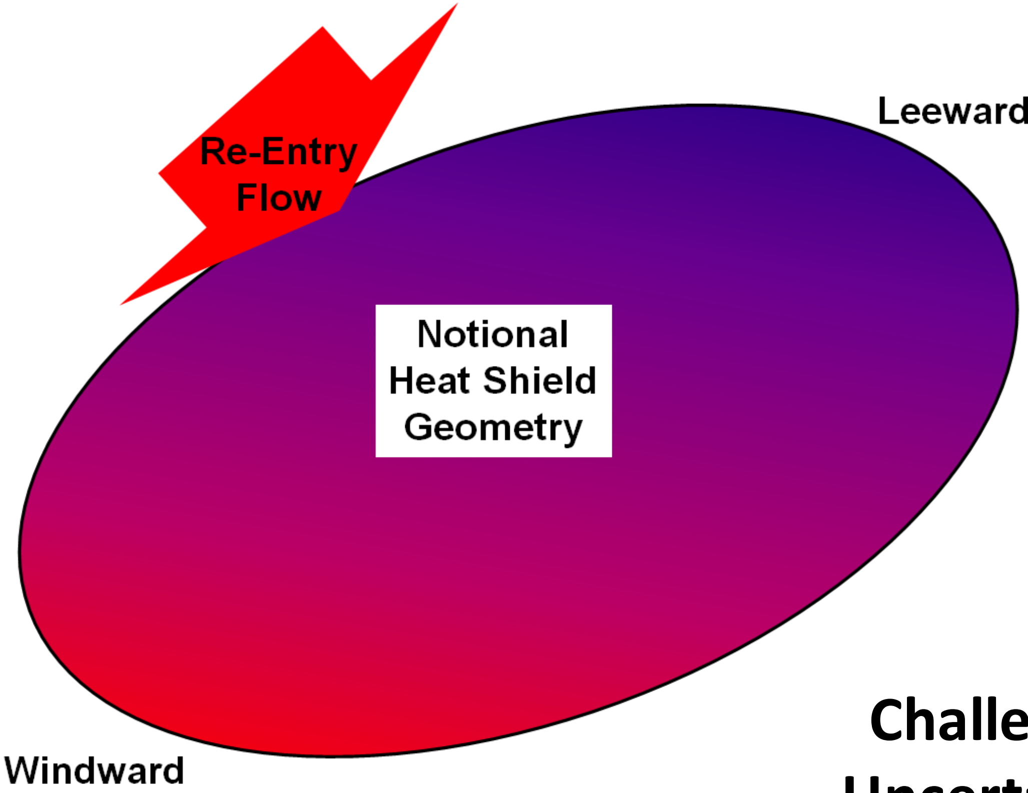
Introduction

- For a typical planetary atmospheric entry / re-entry thermal protection system (TPS):



What does it take to connect design margins with quantified reliability?

Challenges:
Uncertainties
The numerical evaluation of uncertainties
Philosophical issues of uncertainty management

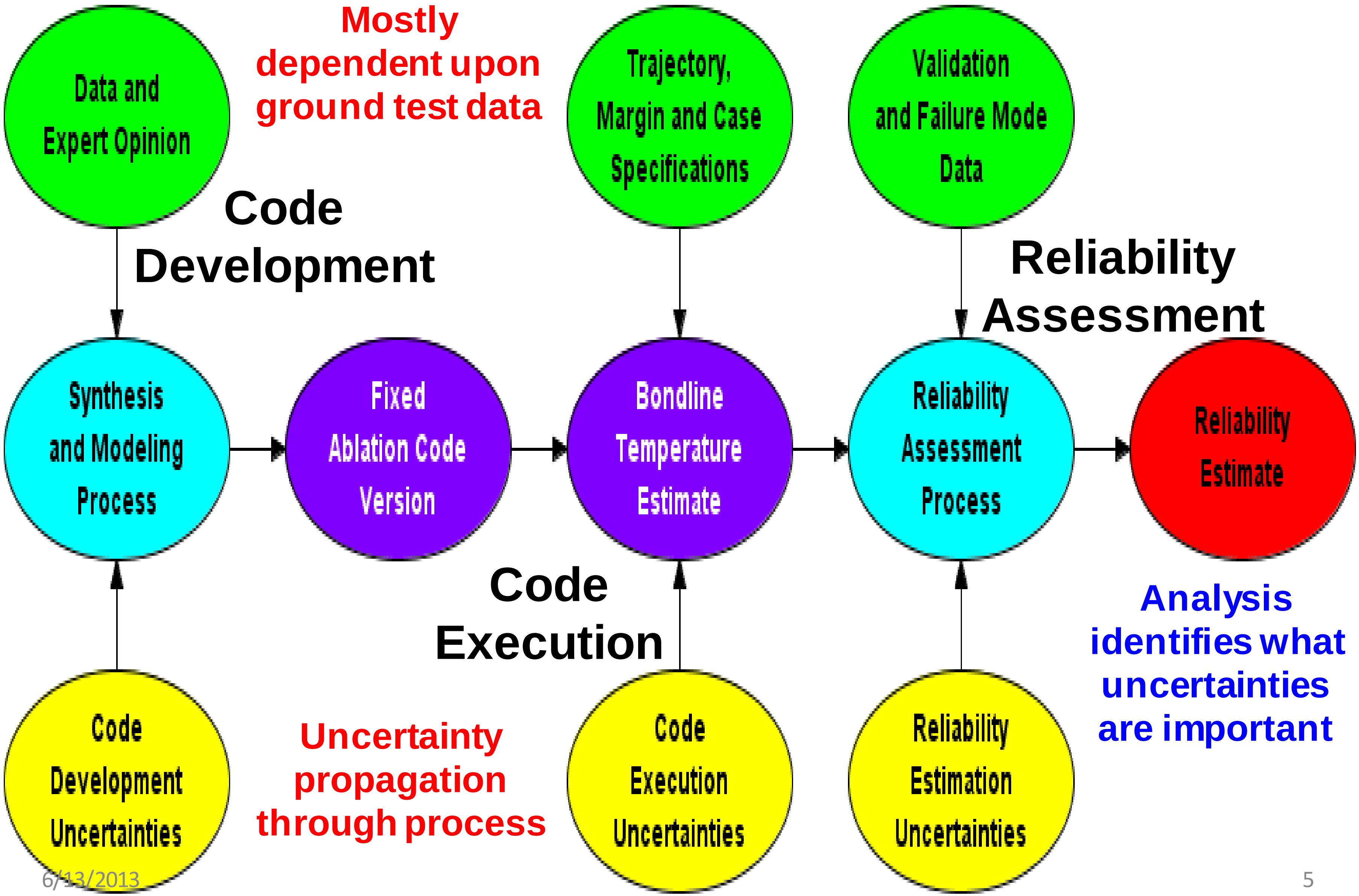
Sample
Challenge Problem

Achieve 99% Reliability with 95% Confidence

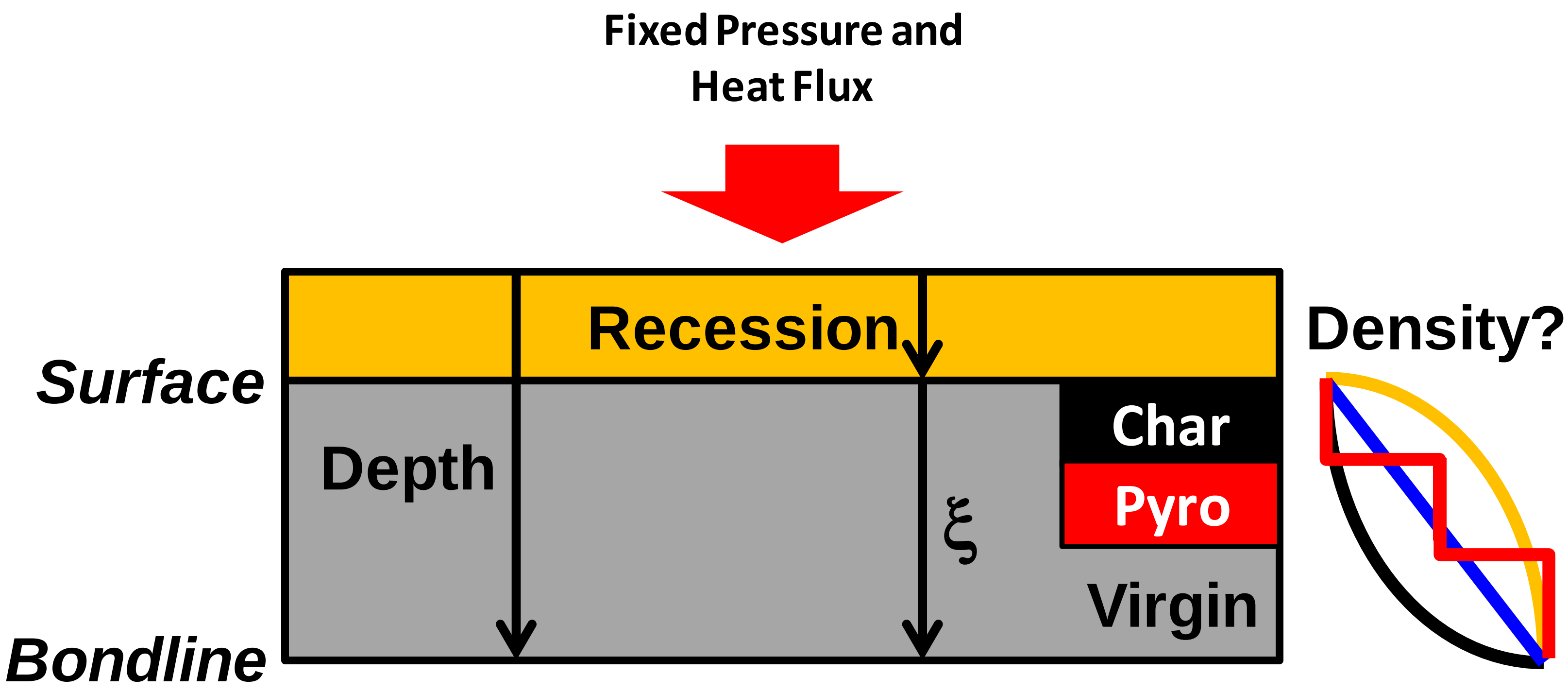
Top Ten List

1. Arc Jet Testing
2. Data issues
3. Material Property Effects / Correlations
4. Trajectory / Orientation
5. Flow Transition
6. Ground to Flight Uncertainty
7. Failure Mode Form
8. Reliability Assessment
9. Reliability Cascade
10. Cost / Benefit modeling

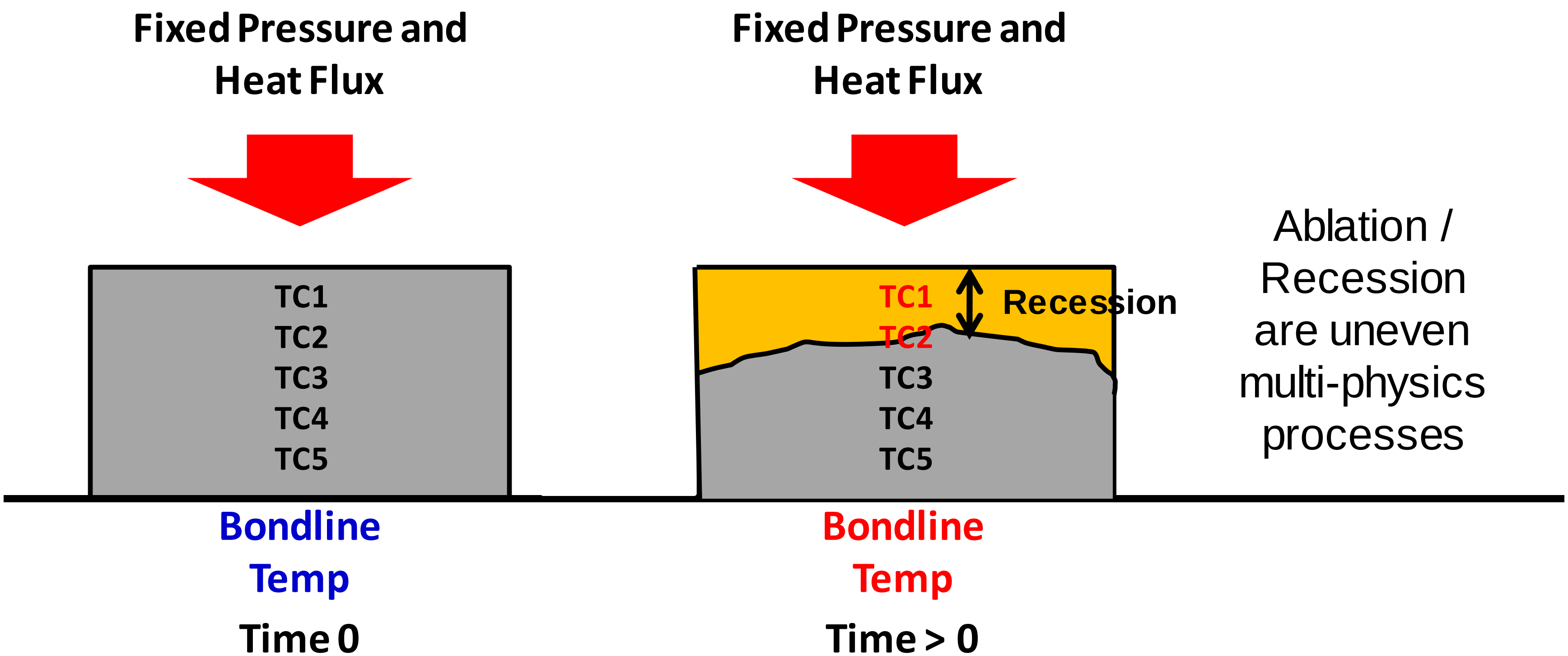
Generalized Reliability Assessment Process



1-D Ablation Model



Arc Jet Ground Testing as an Uncertainty Source



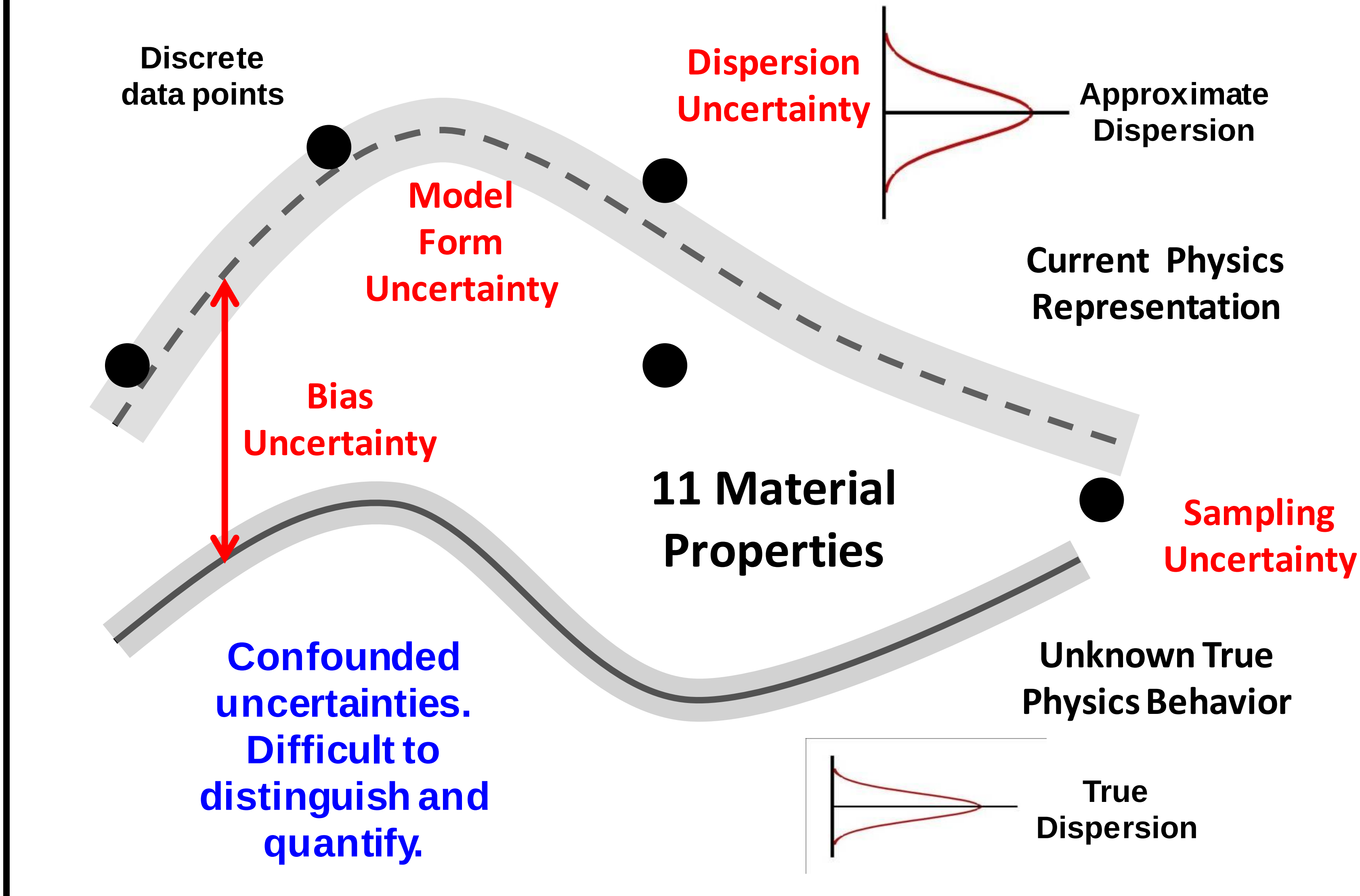
Tests are conducted over a few minutes; some thermocouples (TCX) burn up. The bondline temperature, which increases over time and well beyond the end of the test, is currently used to establish the TPS reliability.

Considerable uncertainty in the bondline temperature estimate. Does this adequately represent the re-entry physics?

Problems With Arc Jet Testing

- Test reproducibility (deepest thermocouple)
  - Test against test, same conditions, same facility
  - **Max COV ~ 38%, Avg COV ~ 7% (deg R)**
- Computational validation (deepest thermocouple)
  - Code against test, same conditions
  - **Max COV ~ 45%, Avg COV ~ 8% (deg R)**
- Facility limitations
- Facility dependent results; e.g., enthalpy effects

Data = Uncertainty



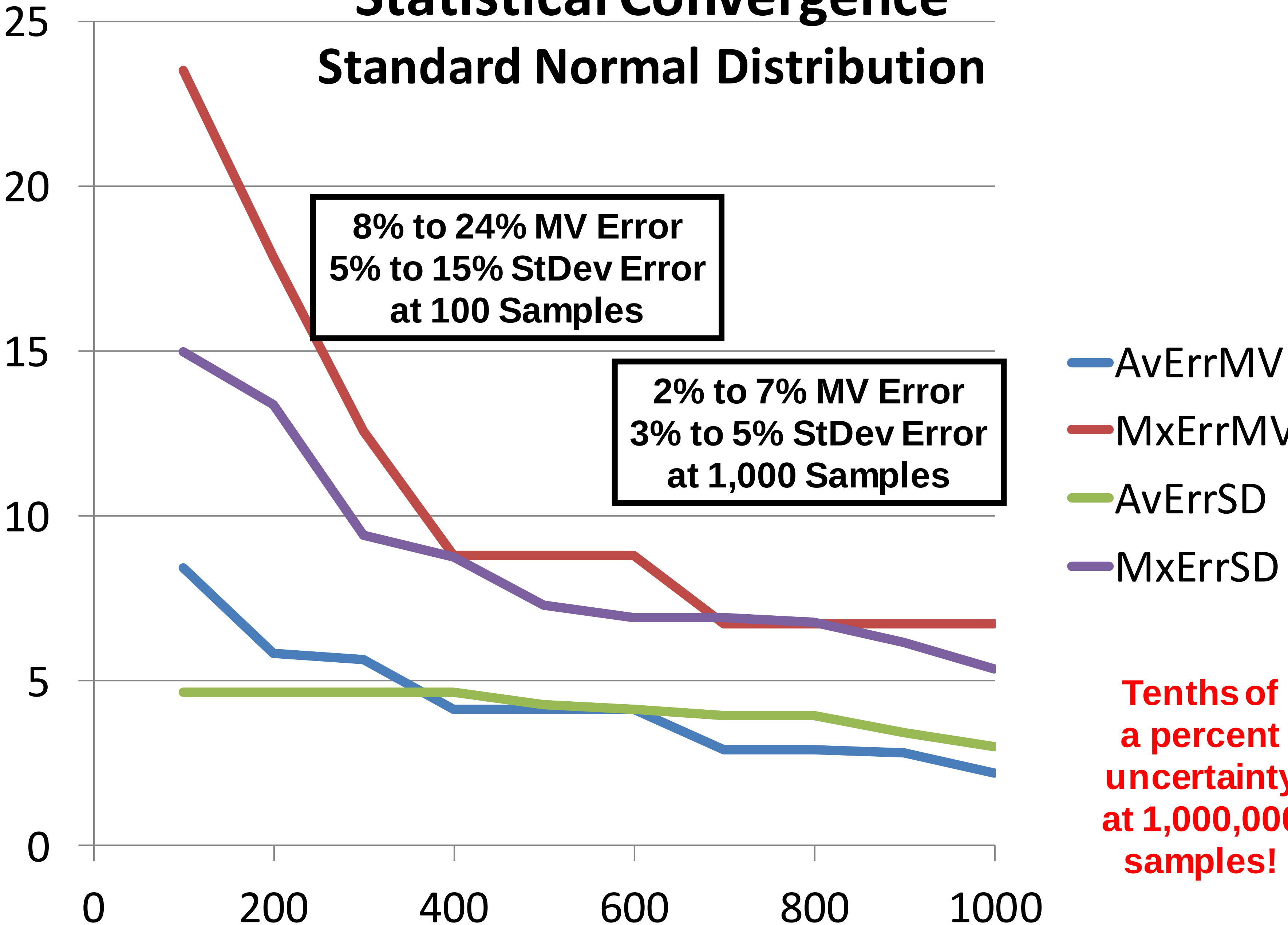
Data Bias

- Little variation within a single data set
- Large variation among various data sets
- Which data set represents the right answer?

- **They all do! Big Uncertainties!**

- **Virgin Thermal Conductivity ~ 18%**
- **Diffusivity ~ 15%**
- **Virgin Specific Heat ~ 14%**
- **Char Emissivity ~ 2%**

Statistical Convergence
Standard Normal Distribution



Tenths of a percent uncertainty at 1,000,000 samples!

11 Material Property Raw Data Sets

- RHOV – virgin density
- RHOC – char density
- XKVRG – virgin thermal conductivity
- XKCHR – char thermal conductivity
- CPVRG – virgin specific heat
- CHCHR – char specific heat
- EMVT – virgin emittance
- EMCT – char emittance
- ZBPRIM – B'c, normalized recession
- ROUGHT – roughness height
- CPGAS – pyrolysis gas enthalpy
- **Complicated picture – raw data from multiple testing sources; strong sample dependence (bias uncertainty) for several variables; separate mean value and dispersion modeling**

Material Property Uncertainties

Variable	COV%	AltCOV%	Max MV Unc%	Max SD Unc%
RHOV	4	4	34	19
RHOC	4	4	70	49
CPVRG	5	16	4	3
CPCHR	10	10	64	47
XKVRG	7.5	7.5	34	23
XKCHR	25	31	34	13
EMCT	2	3	64	40
EMVT	5	5	116	86
ROUGHT	25	25	116	86
ZBPRIM	20	20	5	4
CPGAS	25	29	34	20

Additional Sampling Uncertainties

Sample Material Property Variation Increments

	Temperature		Recession	
Variable	Direction	Delta%	Delta%	Direction
RHOV	Minus	13	5	Minus
RHOC	Plus	5	5	Minus
CPVRG	Minus	4	1	Plus
CPCHR	Plus	2	1	Plus
XKVRG	Plus	11	2	Minus
XKCHR	Plus	37	31	Minus
EMCT	Minus	2	9	Minus
EMVT	Plus	0	0	Plus
ROUGHT	Plus	3	26	Plus
ZBPRIM	Minus	0	36	Plus
CPGAS	Minus	16	6	Minus

< **Need to measure RHOC**

Same variation simultaneously increases temperature and recession

Sample Material Property Correlation Increments

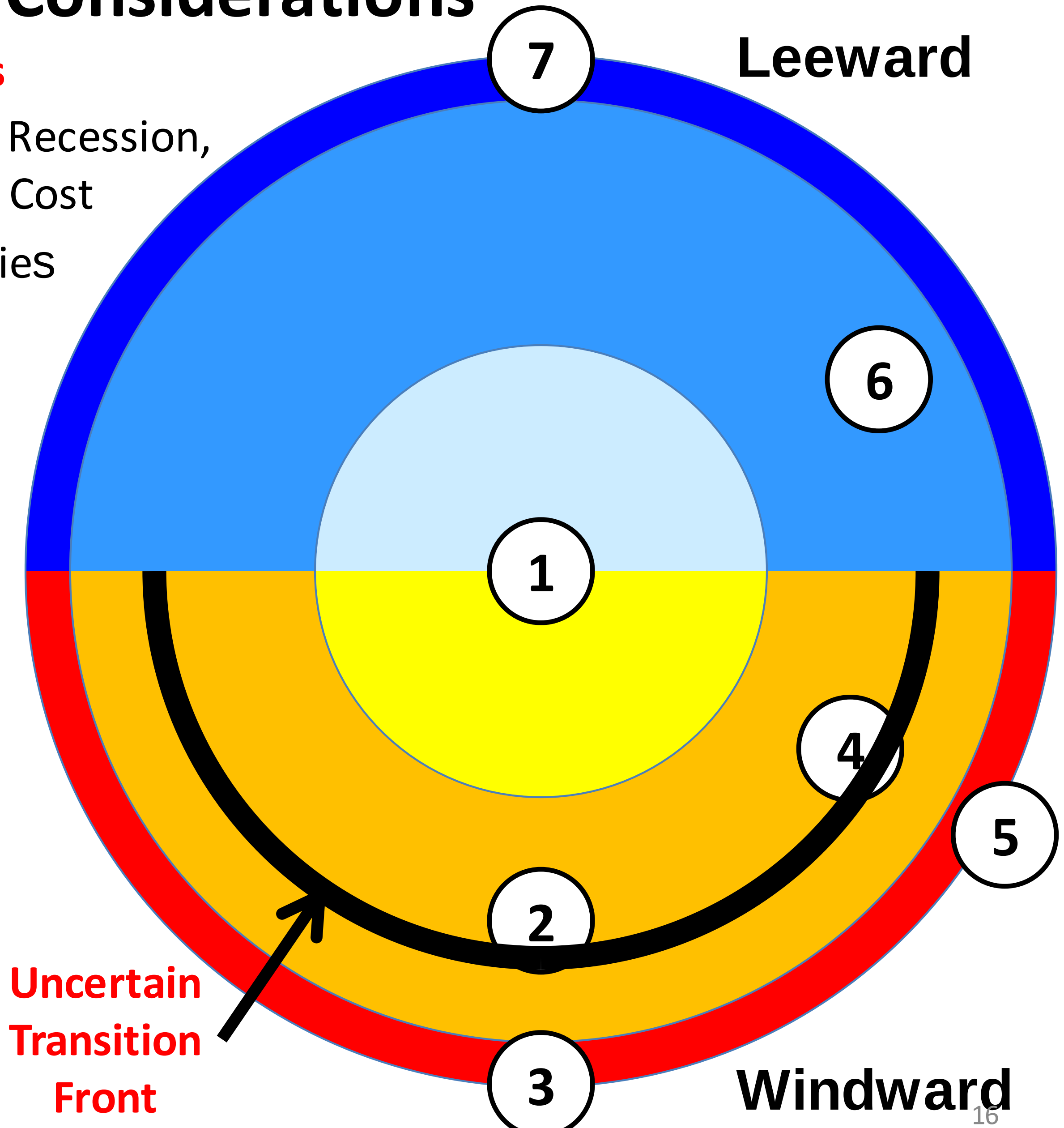
Case	Variable 1	Variable 2	DelRec%	Del%Tmp
1	RHOV	RHOC	11	6
2	RHOV	CPVRG	3	17
3	RHOV	CPCHR	4	12
4	RHOV	XKVRG	7	3
5	RHOV	XKCHR	20	-10
6	RHOV	ZBPRIM	-15	13
7	RHOV	CPGAS	8	22
8	RHOC	CPVRG	-4	3
9	RHOC	CPCHR	-4	6
10	RHOC	XKVRG	-6	10
11	RHOC	XKCHR	-33	46
12	RHOC	ROUGHT	21	9
13	RHOC	ZBPRIM	39	5
14	RHOC	CPGAS	-7	-3
15	CPVRG	CPCHR	-1	2
16	CPVRG	XKVRG	0	-6
17	CPCHR	XKVRG	-1	7
18	CPCHR	XKCHR	-30	38
19	XKVRG	XKCHR	-17	30

Same correlation simultaneously increases temperature and recession

Correlations suggested by expert elicitation

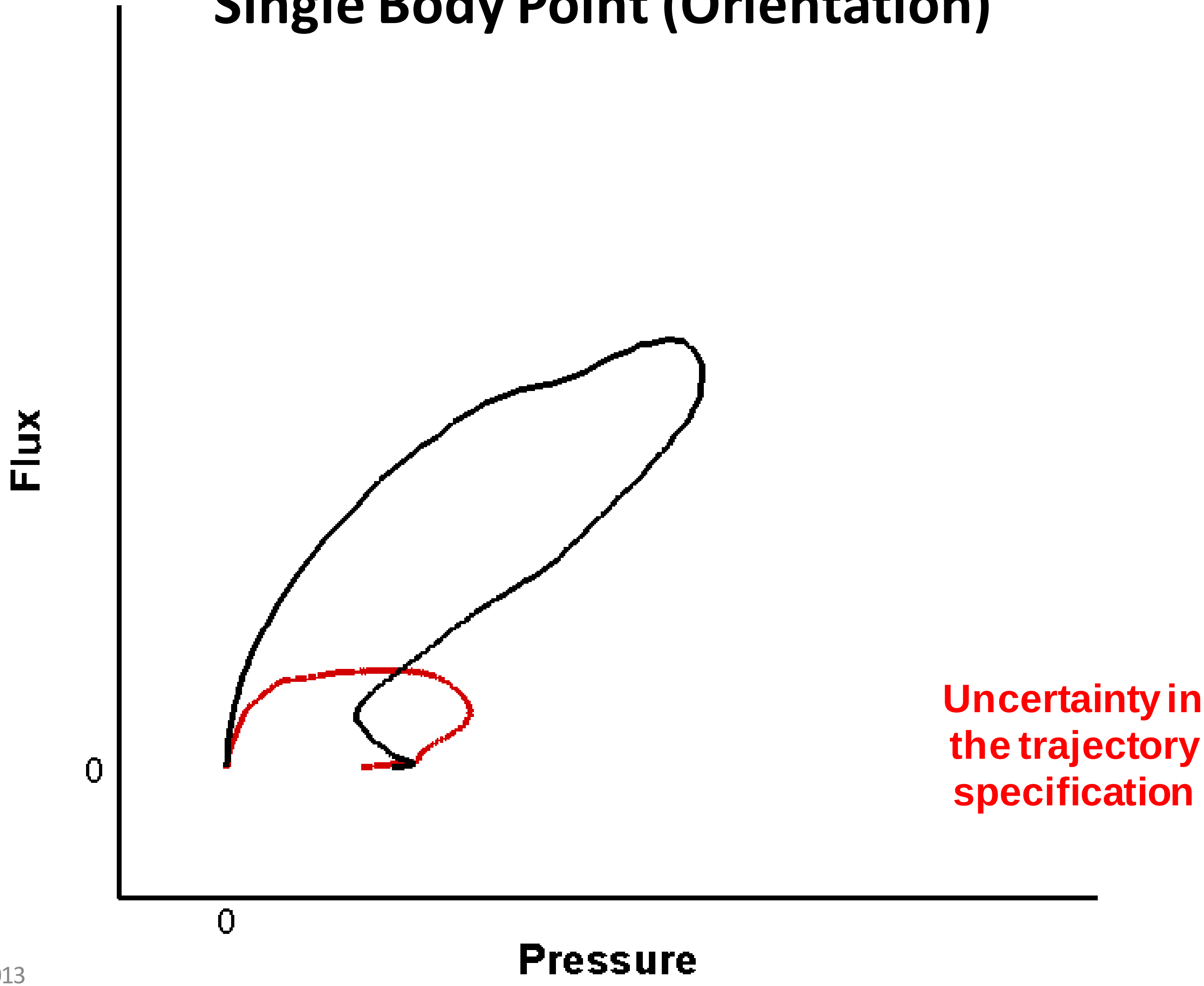
Considerations

- **Complex ablation physics**
- Responses: Temperature, Recession, Reliability, Weight and/or Cost
- 7 points, unique trajectories
- 5 Margin Sets:
  1. **No Margin (Transitional)**
  2. **Turbulent Flow**
  3. **Turbulent + Aero**
  4. **Turbulent + Thermal**
  5. **Turbulent + Aero + Thermal**
- 2 Missions
- **Common and unique uncertainties**



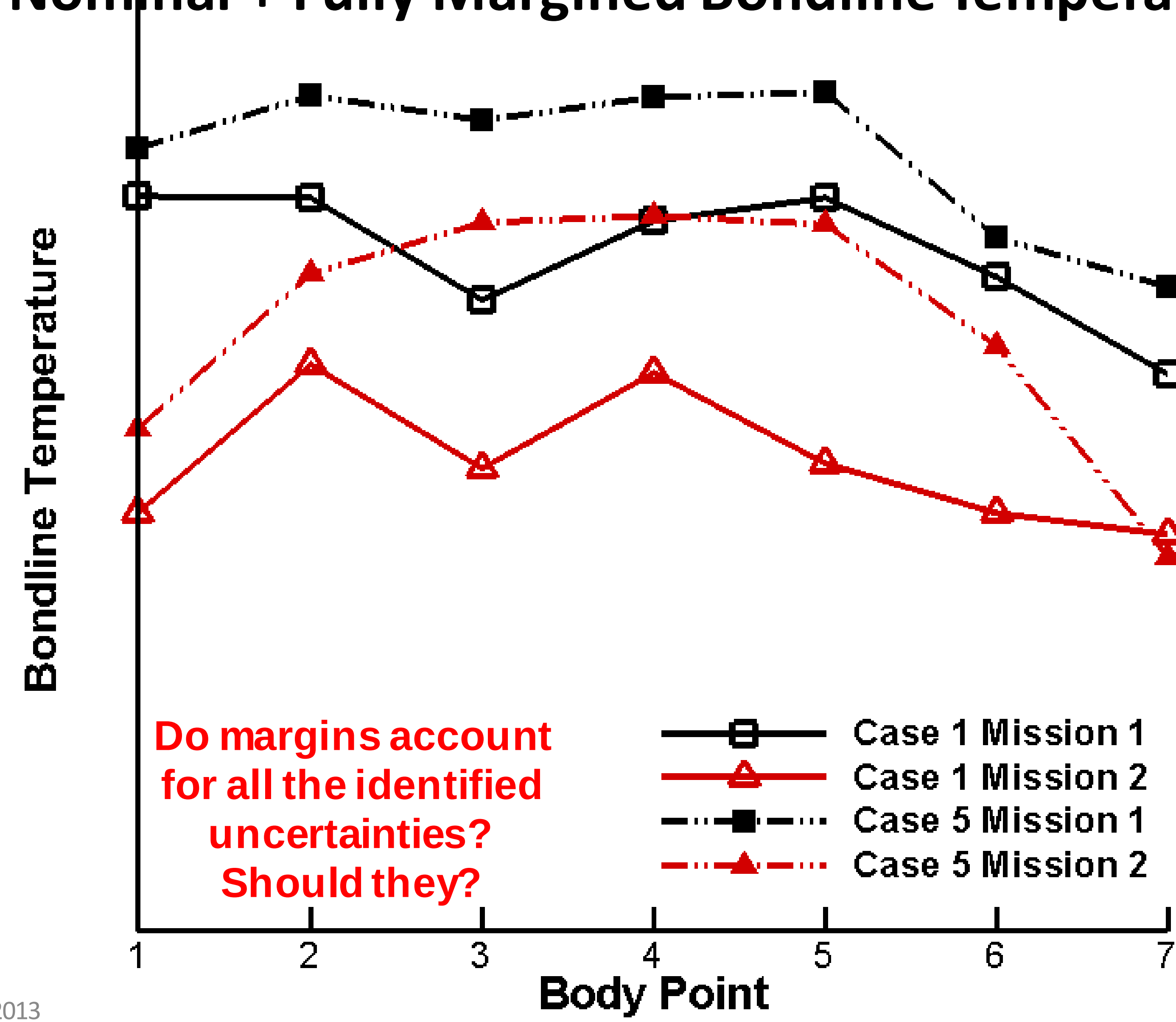
Sample Trajectories

Single Body Point (Orientation)

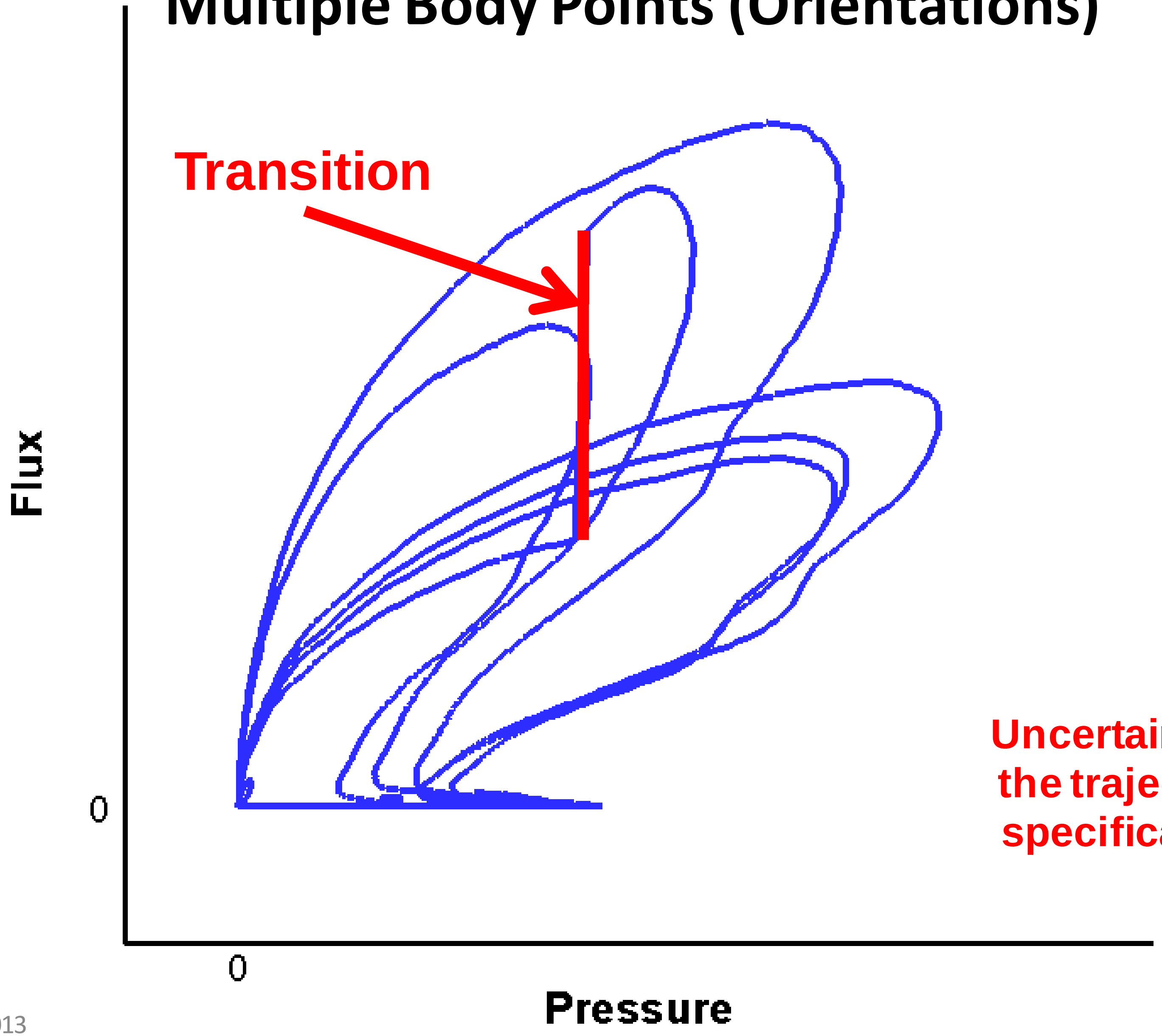


Trajectories (5)

Nominal + Fully Margined Bondline Temperature



Sample Trajectories
Multiple Body Points (Orientations)

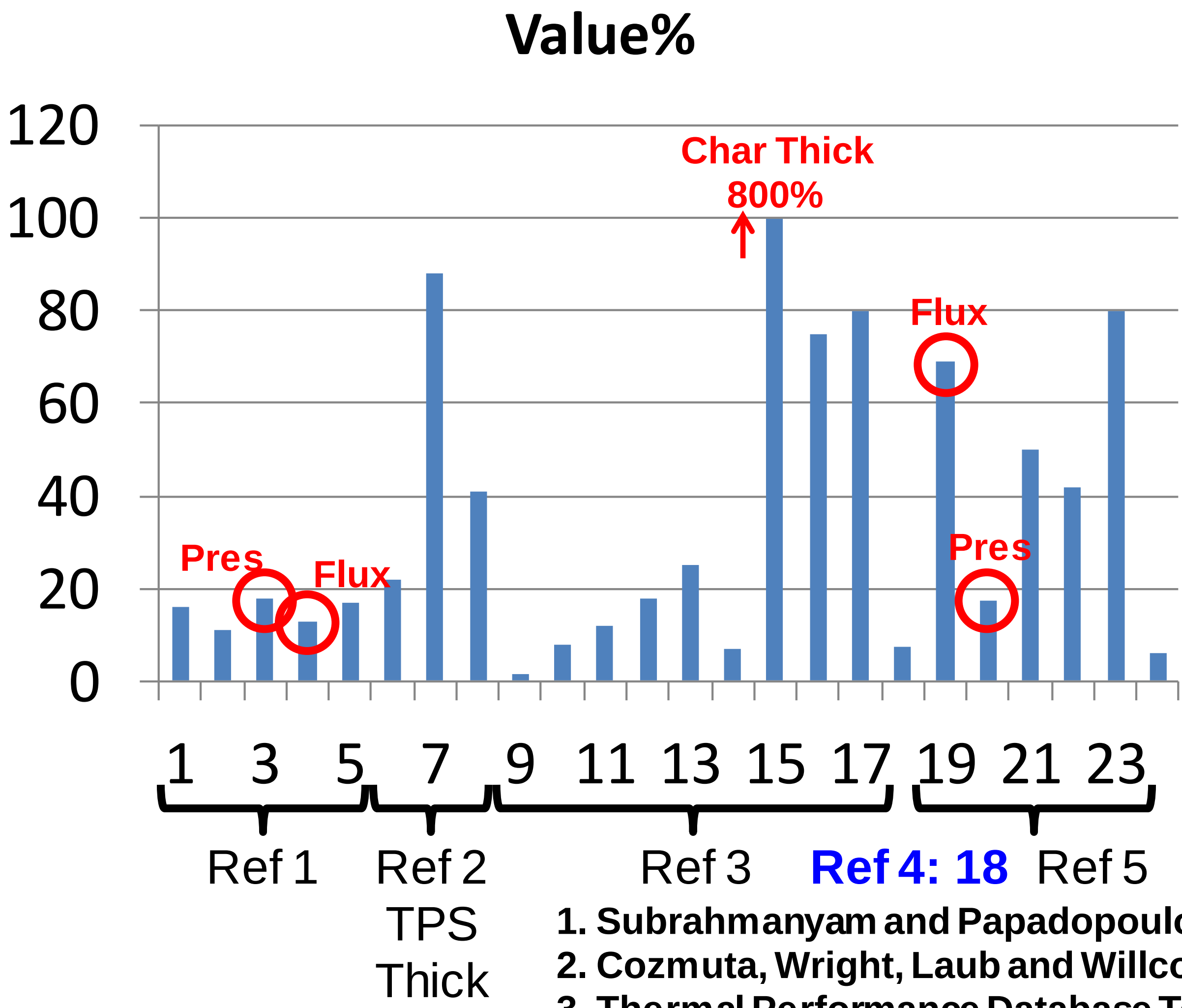


Uncertainty in the trajectory specification

Flow Transition Effects

- 11 material properties
- Random variation
- Temperature COV = 25%
- Recession COV = 13%

Maximum Ground to Flight Corrections from Literature

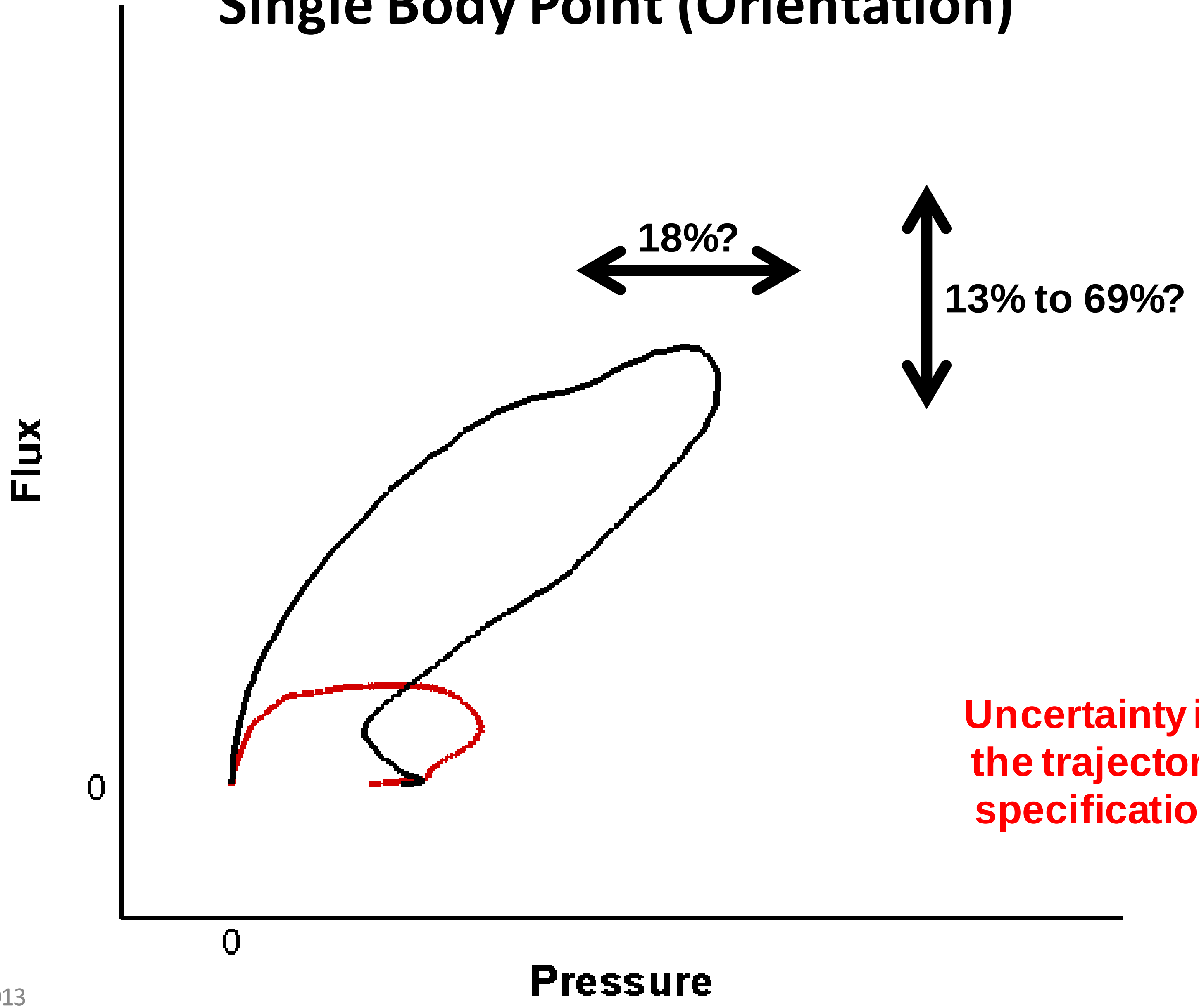


Unc Num	Value%	Uncertainty
1	16	Altitude
2	11	Rey Num
3	18	Stag Point Pres
4	13	Stag Point Flux
5	17	Deceleration
6	22	Stardust
7	88	Pathfinder
8	41	MER
9	1.5	TC1
10	8	TC2
11	12	TC3
12	18	TC4
13	25	TC5
14	7	TC6
15	100	Char Thickness
16	75	Rem Virgin Thickness
17	80	Pyrolysis Gas Blowing Rate
18	7.6	Temperature
19	69	Heat Flux
20	17.5	Pressure
21	50	Temperature
22	42	Char Thickness
23	80	Density
24	6.25	Axial Force Cief

1. Subrahmanyam and Papadopoulos
2. Cozmuta, Wright, Laub and Willcockson
3. Thermal Performance Database Team
4. Mahzari, Braun and White
5. Murray

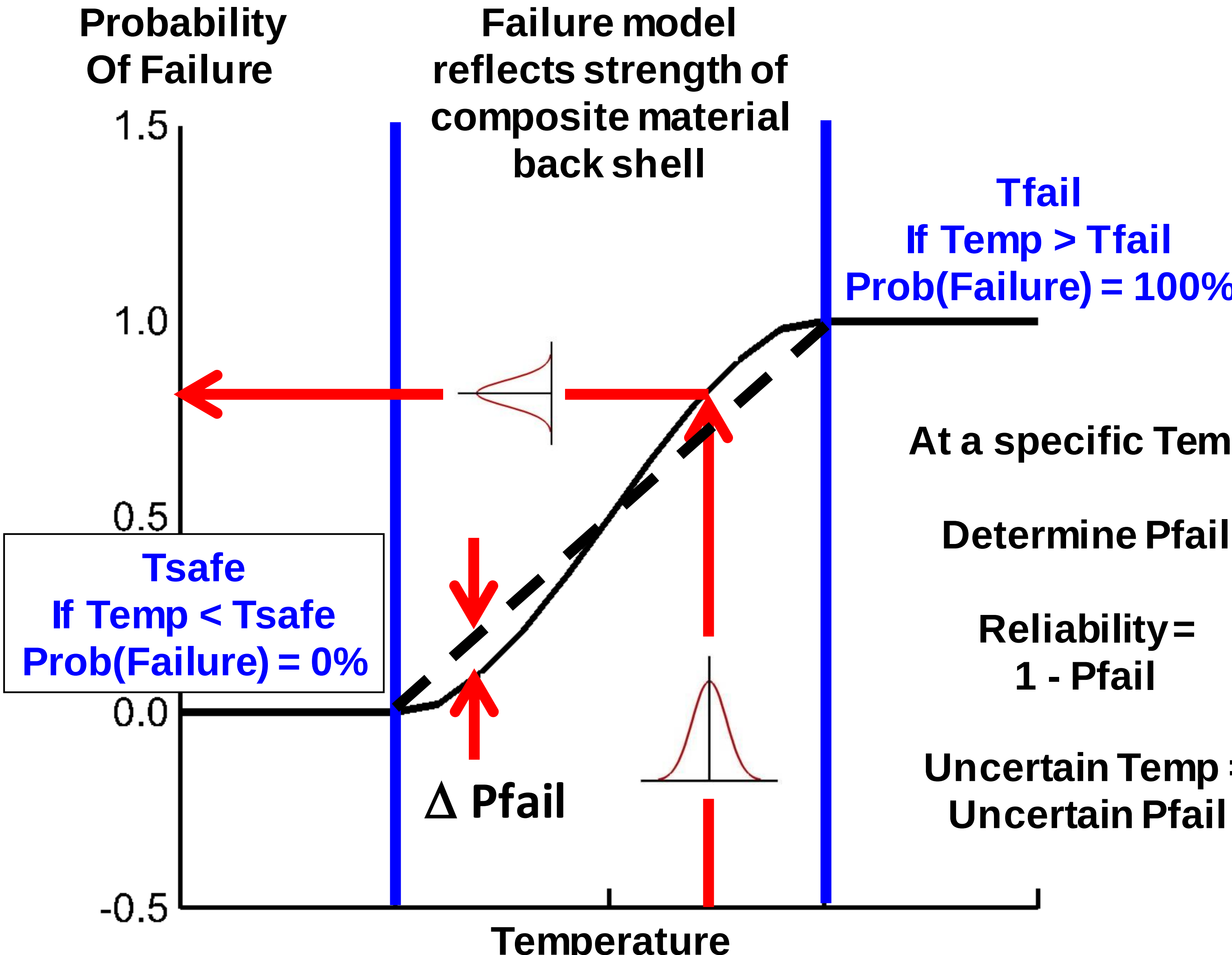
Sample Trajectories

Single Body Point (Orientation)



Uncertainty in the trajectory specification

Notional Failure Mode Model



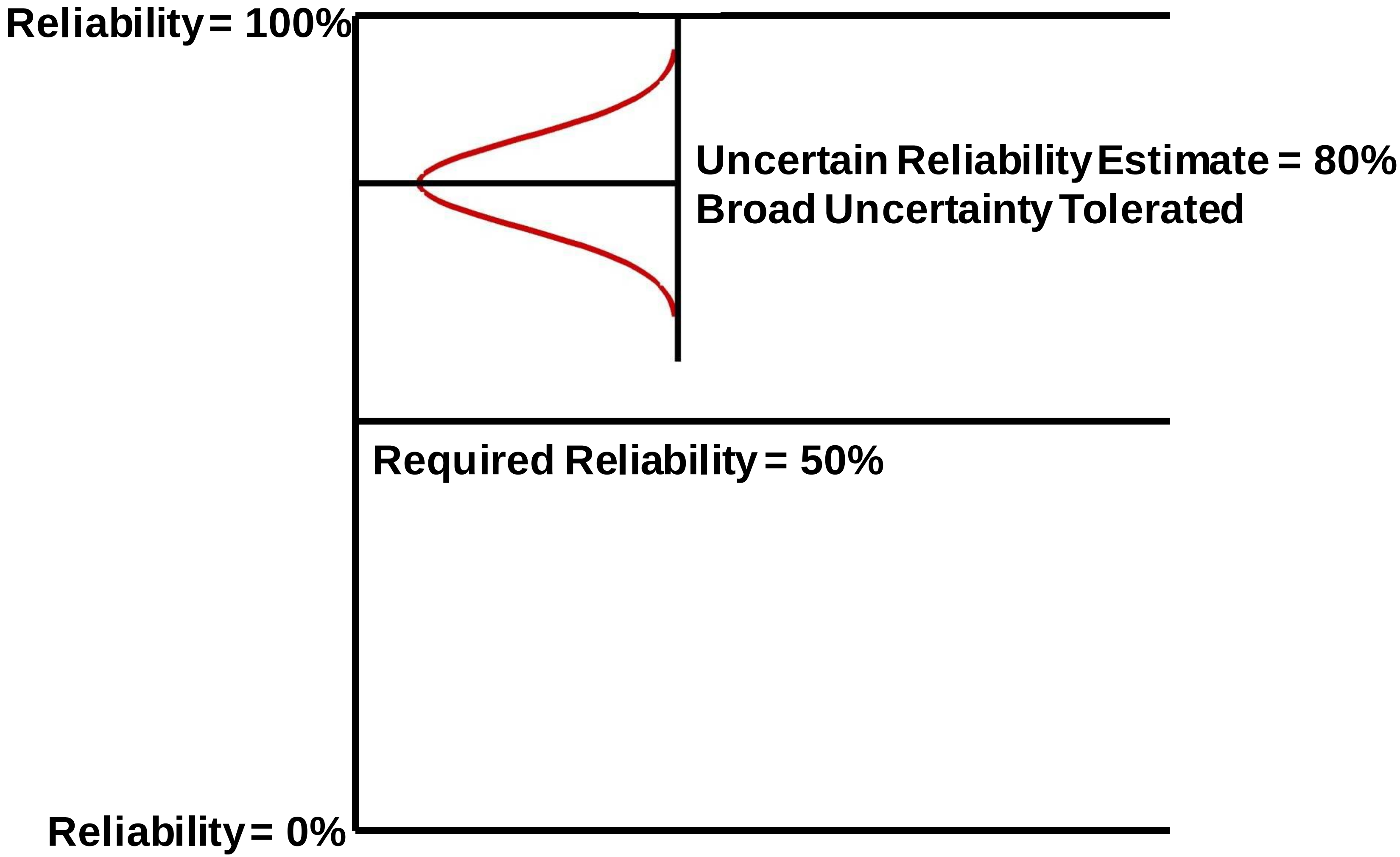
At a specific Temp,

Determine Pfail

Reliability =
1 - Pfail

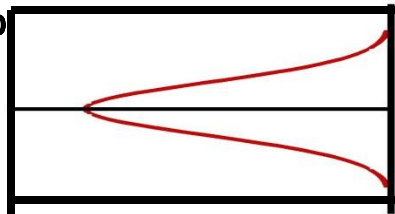
Uncertain Temp =
Uncertain Pfail

Reliability Estimation



Reliability Estimation

Reliability = 100%



Uncertain Reliability Estimate = 95%
Limited Uncertainty Tolerated

Required Reliability = 90%

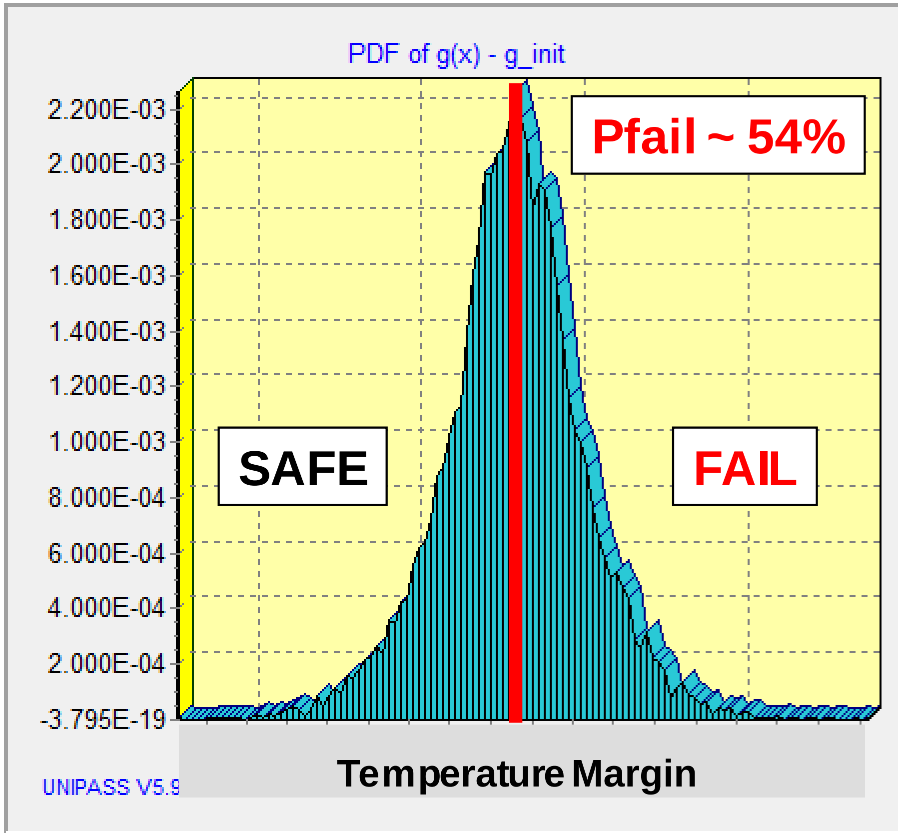
Less tolerance exists for uncertainty in the reliability estimate as the Required Reliability approaches 100%

Req. Rel. = 90%, Total Uncertainty ~ 6%
Req. Rel. = 99%, Total Uncertainty ~ 0.6%
Req. Rel = 99.9%, Total Uncertainty ~ 0.06%

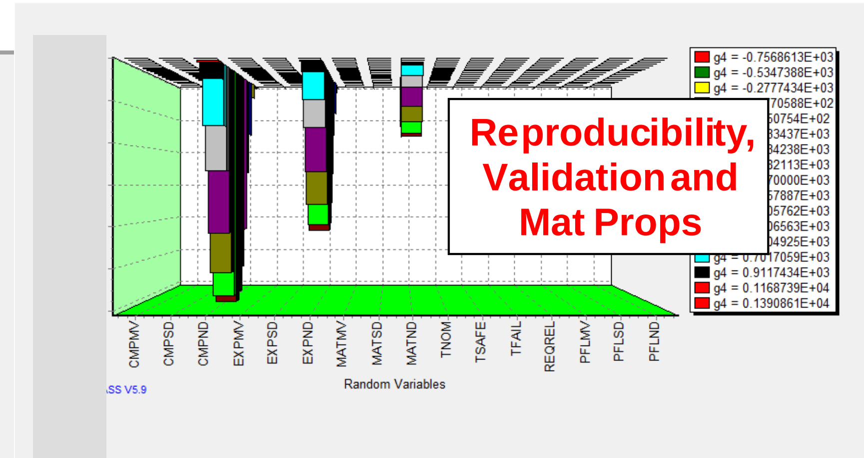
Propagates backward through system

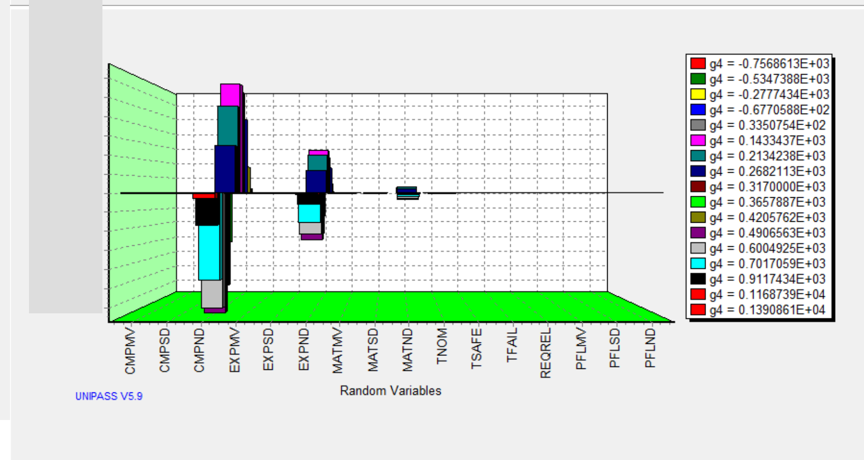
Reliability = 0%

Notional Temperature PDF and Sensitivities



Sensitivities wrt Mean Value

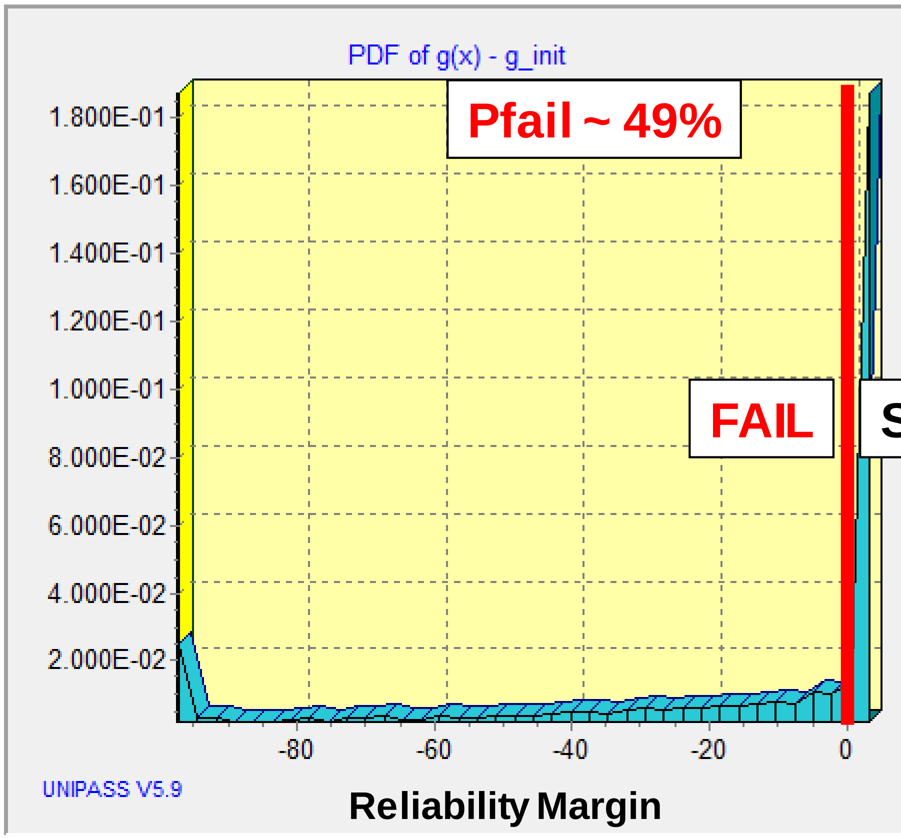




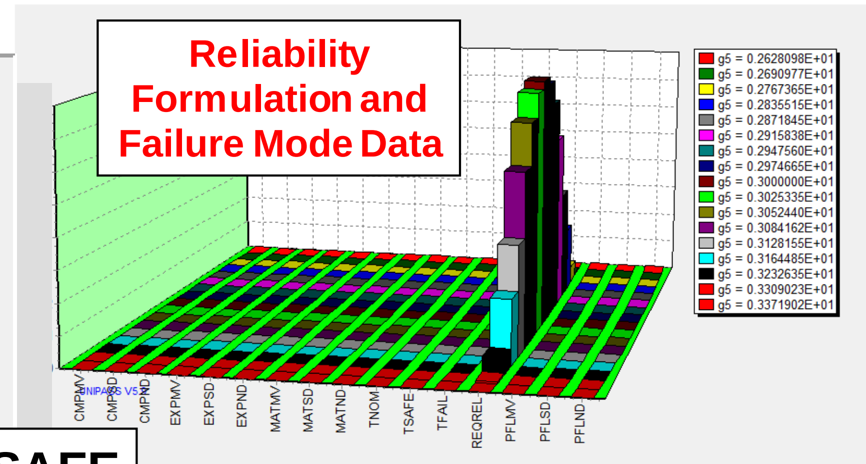
Sensitivities wrt Standard Deviation

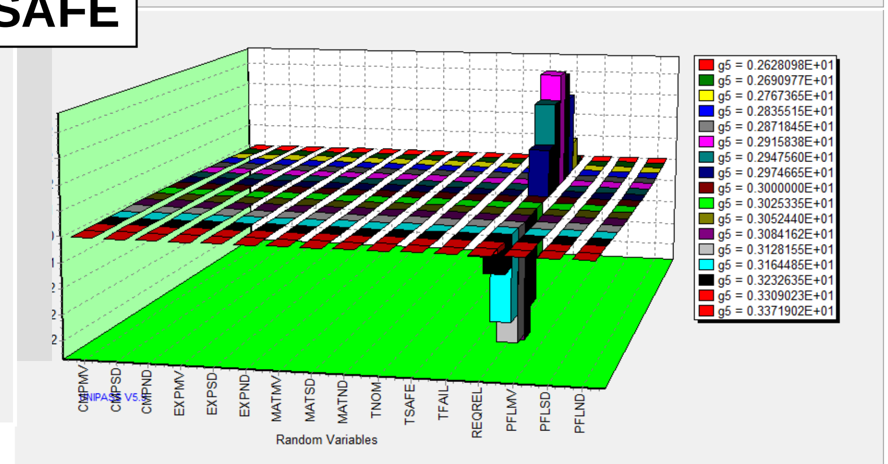
Sensitivities different wrt Mean Value and Dispersion behaviors

Notional Reliability PDF and Sensitivities



Sensitivities wrt Mean Value



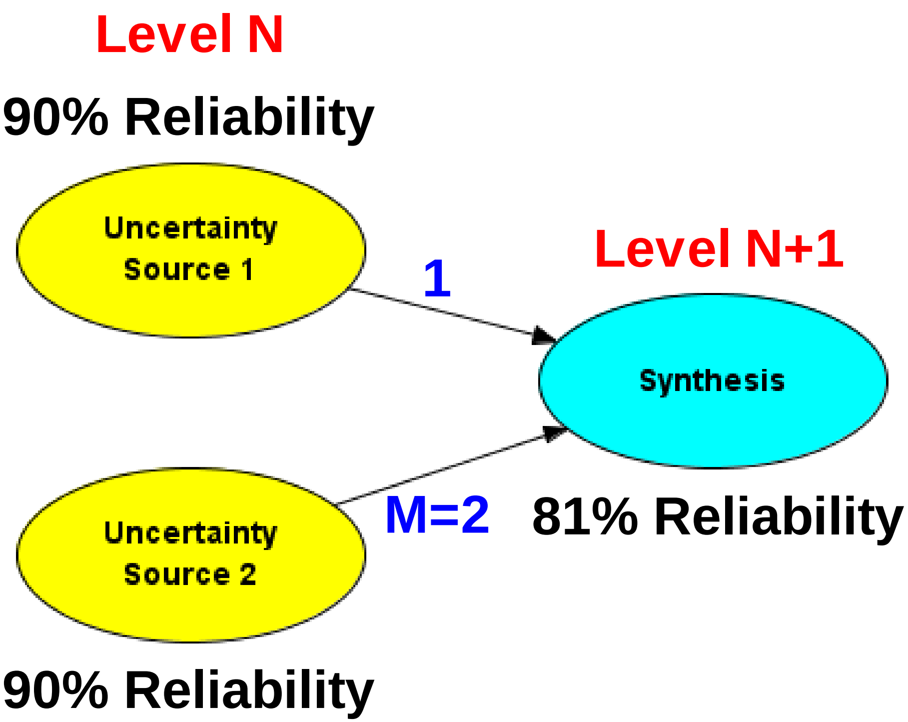


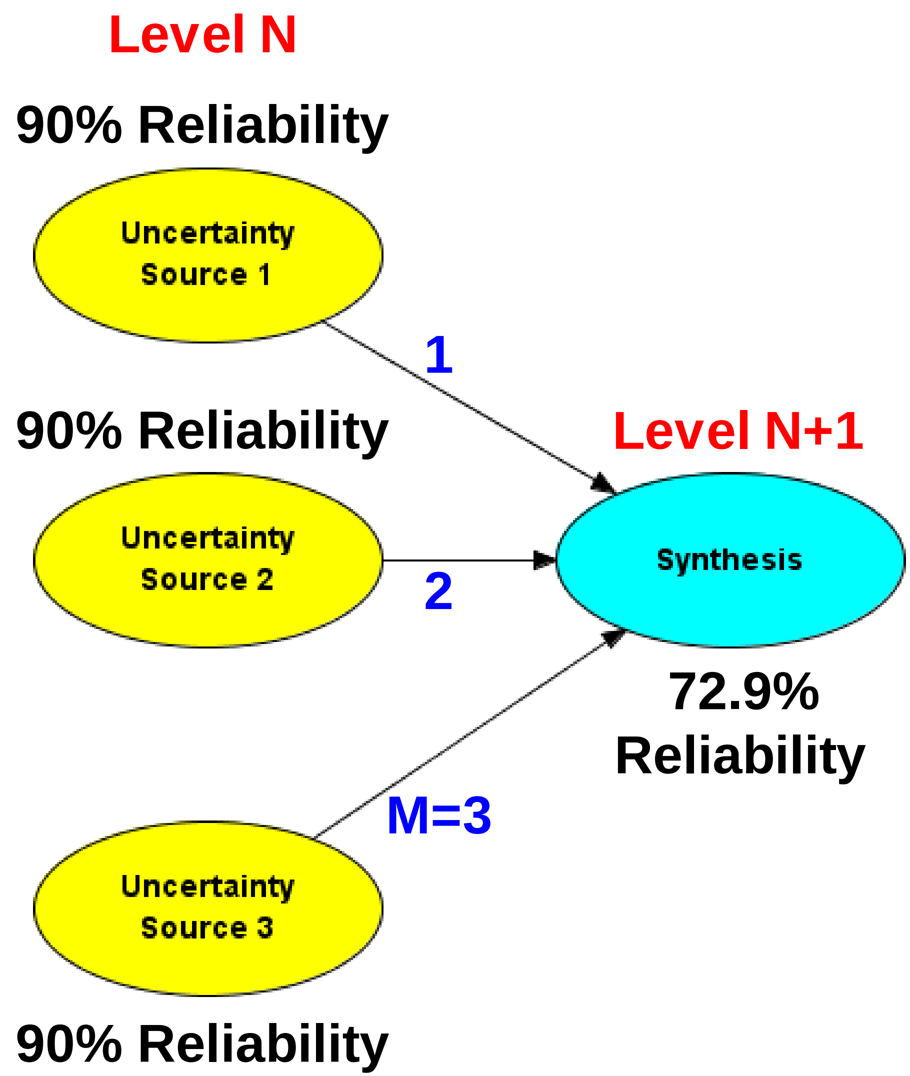
Sensitivities wrt Standard Deviation

Sensitivities different for temperature and reliability

Cascading Reliability Requirements
M Independent Uncertainty Sources

Propagates backward through system





$$ReqRel_N = (ReqRel_{N+1})^{1/M}$$

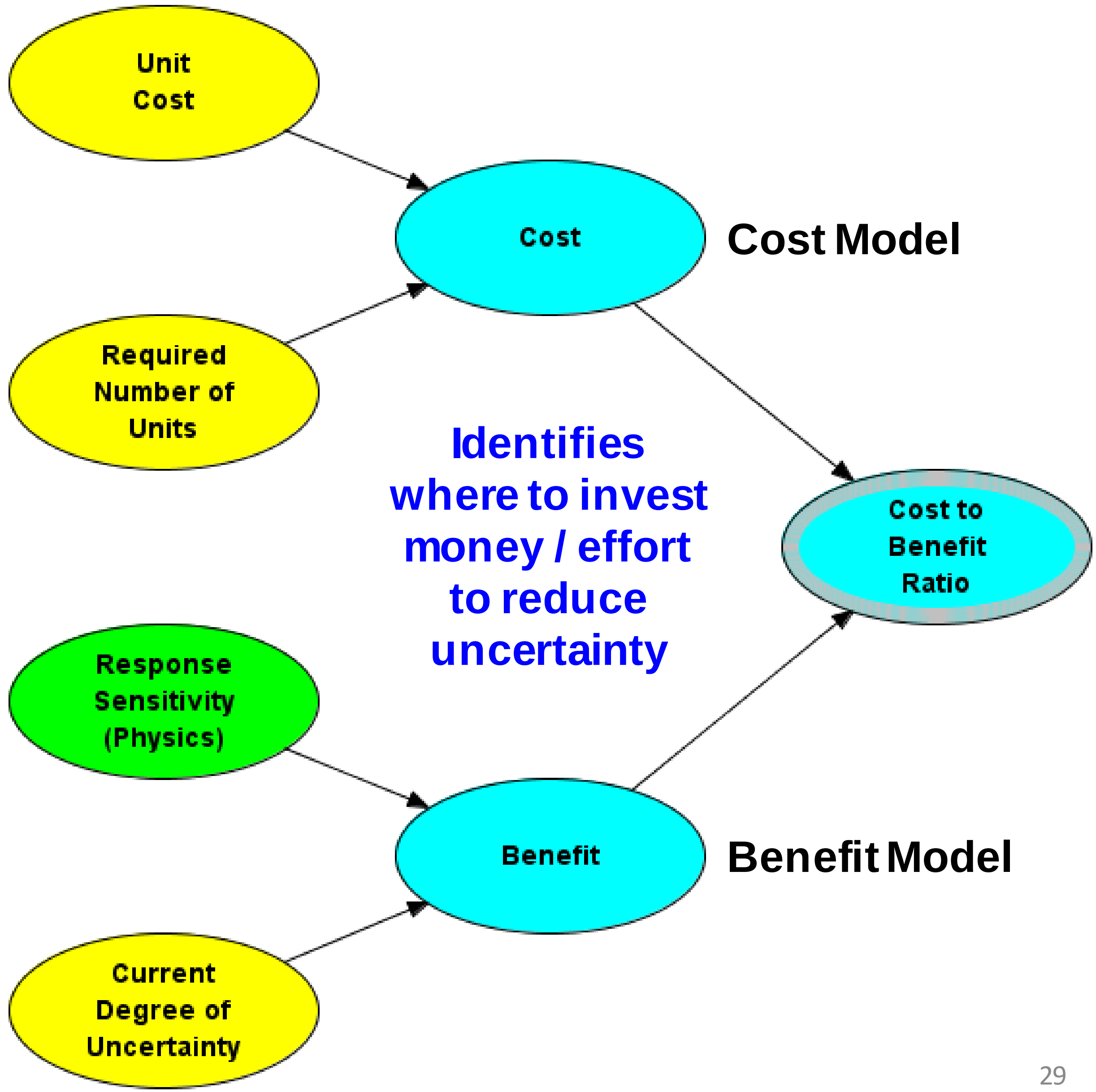
Generic Cost to Benefit Ratio Evaluation

What to buy?
What's the cost?

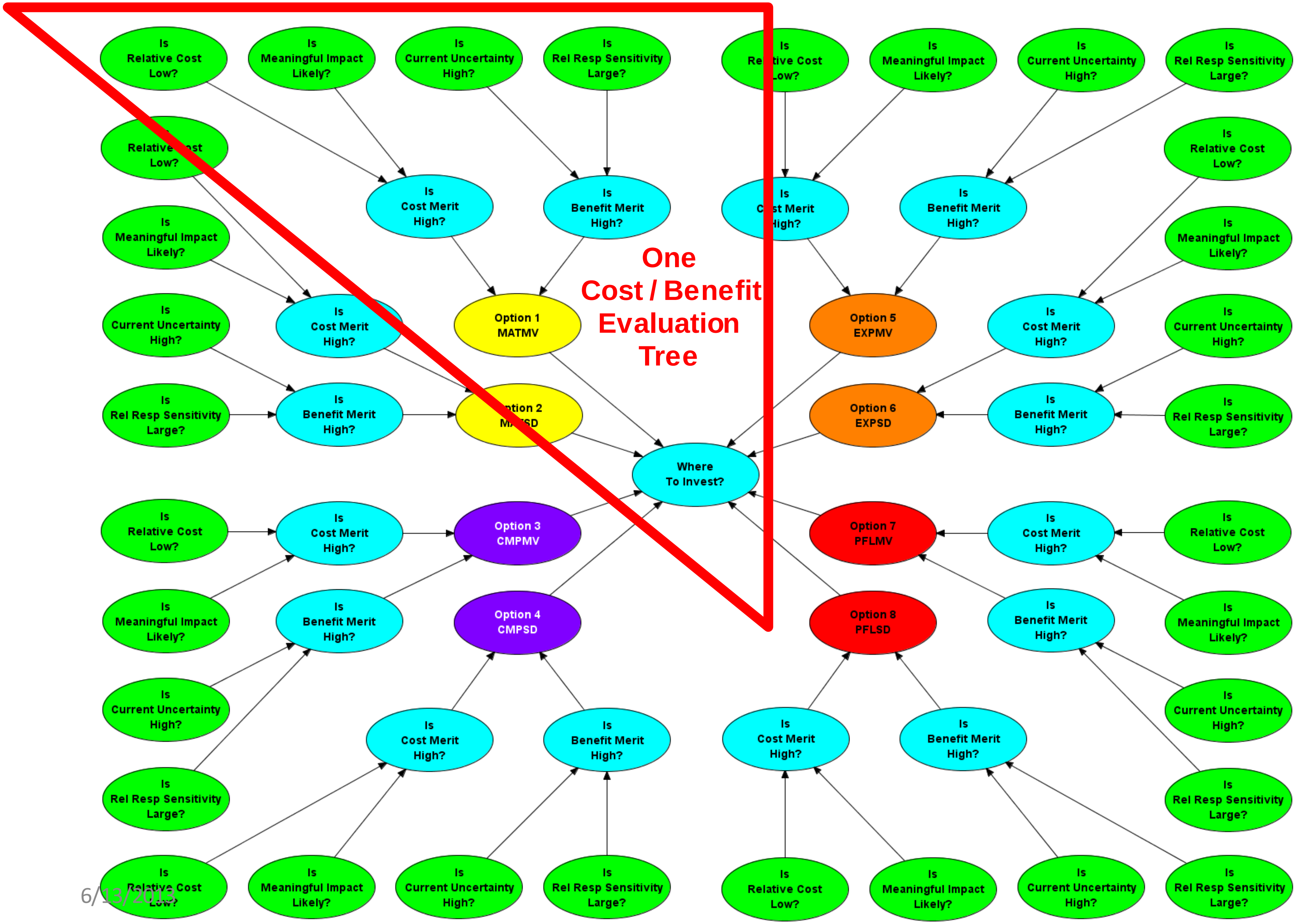
How many
do we need?

What can it do?

Why buy this and
not something else?



8-Factor Resource Allocation Process



Summary

- Discussed uncertainty source identification / quantification
- Discussed uncertainty source propagation to responses
- Very different sensitivities for reliability and temperature
  - **Temperature: data reproducibility and validation metrics**
  - **Reliability: reliability formulation and failure mode data uncertainty**
- Discussed an approach for cost / benefit evaluation

- ***Raised important questions***
- ***Answers are totally dependent upon assumptions used***
- ***Difficult to generalize numerically***
- All based on ***single subsystem*** analyses

Recommendations

- Use an advisory committee (or follow-on workshops) to:
  - Identify / quantify uncertainty sources
  - Propose mitigations for each uncertainty source
  - Propose cost models for each mitigation
  - Propose benefit models for each mitigation
  - Develop community consensus
- Implement above using Probabilistic / Bayesian methods
- ***Balanced*** uncertainty management process across system
  - **Must repeat this kind of analysis across all subsystems**
- Seek robustness in uncertainty management
- Seek simplicity in cost and benefit modeling
- ***Define the reliability that can be achieved***
- ***Define the level of confidence that can be achieved***
- ***Design the design process for high confidence validation!***

Thank you!

Questions?